ELECTRON BEAMS AND LANGMUIR TURBULENCE IN SOLAR TYPE III RADIO BURSTS OBSERVED IN THE INTERPLANETARY MEDIUM

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ABSTRACT. The ISEE-3 spacecraft has provided *in situ* observations of electron beams, plasma waves, and associated solar type III radio emission in the interplanetary medium near 1 AU. These observations show that electron beams are formed by the faster electrons arriving before the slower ones, following an impulsive injection at the Sun. The resulting bump-on-tail in the reduced one-dimensional distribution function, $f(v_\parallel)$, is unstable to the growth of electrostatic electron plasma (Langmuir) waves. The Langmuir waves are observed to be highly impulsive in nature. The onset and temporal variations of the observed plasma waves are in good qualitative agreement with the wave growth expected from the evolution of measured $f(v_\parallel)$. However, far higher Langmuir wave intensities are predicted than are detected. In addition, the lack of obvious plateauing of the bump-on-tail suggests that the waves have been removed from resonance with the beam electrons by some wave-wave interaction. Bursts of low frequency, 30−300 Hz (in the spacecraft frame) waves are often found coincident in time with the most intense spikes of the Langmuir waves. These low-frequency waves appear to be long-wavelength ion acoustic waves, with wave number approximately equal to the beam-resonant Langmuir wave number. The observations suggest several possible interpretations: modulational instability, electrostatic decay instability, and electromagnetic decay instability; but none of these are fully consistent with the observations. Microstructures, too short in duration to be resolved by present experiments, have been invoked as an explanation of the phenomenon. Experiments are currently being developed to study these processes using fast wave-particle correlation techniques.

INTRODUCTION

Type III solar radio bursts (Figure 1) are produced by fast particles ejected from the Sun (*Wild,* 1950*a,b*). The primary radiation is believed to occur at either the fundamental, f_{p-}, or the harmonic, $2f_{p-}$, of the local electron plasma frequency. The bursts are characterized by a rapid drift from high to low frequency which is attributed to the decreasing electron plasma frequency f_{p-} encountered by the fast particles as they

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move outward through the solar corona. It has been confirmed that electrons with energies from a few keV to a few tens of keV, often from solar flares, are responsible for the type III radio emission (*Lin,* 1970, 1974; *Alvarez et al.,* 1972; *Frank and Gurnett,* 1972; *Lin et al.,* 1973).

Gurnett and Anderson (1976, 1977) have also observed intense electron plasma oscillations in association with type III radio bursts, apparently confirming a basic mechanism first proposed by *Ginzburg and Zheleznyakov* (1958). In this mechanism, type III radio bursts are produced by a two-step process in which intense electrostatic electron plasma oscillations are first excited by a two-stream instability caused by the fast electrons (Figure 2*a*), and then these plasma oscillations decay into electromagnetic radiation because of nonlinear interactions. Electrons slightly faster (slower) than the wave phase velocity $v_\phi = \omega/k$ will lose (gain) energy to (from) the plasma wave. Thus if a bump is present on the tail of the distribution (Figure 2*b*) so that there are more electrons supplying energy to the wave than taking energy away (i.e., a positive slope in the distribution) the wave will grow. If the plasma waves grow rapidly enough, the bump will be flattened out, a process known as "quasi-linear relaxation" or "plateauing." *Sturrock* (1964) pointed out that in a homogeneous beam-plasma model the fast particle stream, i.e., a bump-on-tail distribution, is so rapidly diffused in velocity space by the intense plasma waves that a coherent stream would only be able to travel a few thousand kilometers from its source before it is plateaued. A major question then for type III burst theory is: What allows the stream to propagate from the Sun to well past 1 AU, as observed?

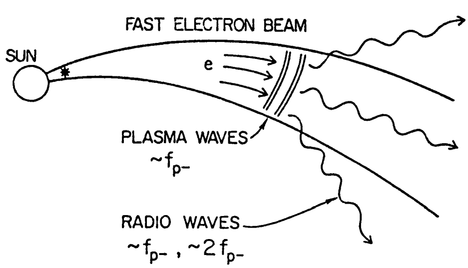

Figure 1. Schematic of the solar type III radio burst mechanism.

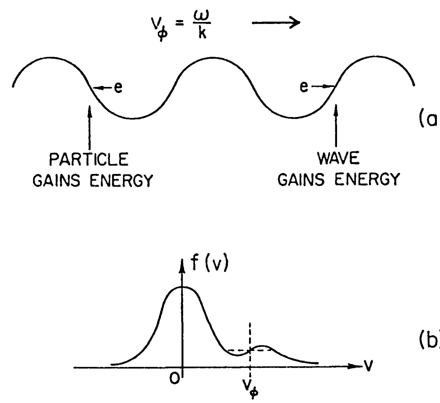

Figure 2. *(a)* Schematic illustration of the interaction between the plasma wave and particles. In the rest frame of the wave particles going slightly faster (slower) will lose (gain) energy to (from) the wave. *(b)* If there is a positive slope in the particle distribution at the wave phase velocity the wave can grow. As the wave grows it will eventually flatten or "plateau" the bump.

Observations show that the stream is highly inhomogeneous with the bump-on-tail distribution produced by the faster electrons running ahead of the slower ones. At a given distance from the fast particle source, the bump in the distribution moves from high to low velocity with time. Thus, one possibility is that plasma waves produced by the positive slope portion of the distribution may not build up to sufficient amplitudes to interact with the bump before the bump has moved to lower velocities. Also, the plasma waves produced with a given phase velocity at time t_1 by a positive slope may be reabsorbed at a later time t_2 when a negative slope is present. Several numerical model calculations suggest that the quasi-linear relaxation (plateauing) will occur, but reabsorption of the plasma waves is important in enabling the stream to propagate large distances without catastrophic energy loss (*Magelssen and Smith,* 1977; *Takakura and Shibahashi,* 1976; *Grognard,* 1980).

Another possibility is that various nonlinear wave-wave interactions may be important in shifting the plasma waves to different wave numbers where they are no longer resonant with the beam electrons; this would allow the electrons to travel large distances without catastrophic energy loss. These mechanisms include induced scattering of the Langmuir waves off ion clouds (*Kaplan and Tsytovich,* 1968), parametric instabilities such as oscillating two-stream instability (*Papadopoulous et al.,* 1974; *Papadopoulous,* 1975; *Bardwell and Goldman,* 1976), and strong turbulence processes such as soliton collapse (*Zakharov,* 1972; *Nicholson et al.,* 1978; see also reviews by *Goldman,* 1983, 1984).

In addition, density irregularities and ion acoustic waves already present in the solar wind can significantly affect the growth and saturation of beam-driven Langmuir waves, to the point of stabilizing the beam (*Escande and de Genouillac,* 1978; *Goldman and DuBois,* 1982; *Russell and Goldman,* 1983; *Muschietti et al.,* 1985).

Because type III bursts propagate to 1 AU and beyond, direct *in situ* observations of the electron beam, Langmuir waves and low frequency waves, and associated type III radio emission in the interplanetary medium near 1 AU are available from spacecraft. In this paper I review these observations and their implications for the plasma processes underlying type III bursts. Although type III bursts are among the best studied of any solar plasma phenomena, we shall see that it is still not well understood, and that a variety of plasma phenomena may be involved. Finally, we discuss briefly observations planned for the future.

OBSERVATIONS OF ELECTRON BEAMS AND LANGMUIR WAVES

The primary observations were obtained from the International Sun Earth Explorer (ISEE)-3 spacecraft, which was located in the solar wind approximately a million miles upstream from the Earth. The radio and plasma wave measurements are from the joint TRW-JPL-Iowa plasma wave instrument on ISEE-3, and the electron measurements are from the University of California, Berkeley, energetic particle instrument on ISEE-3.

Figure 3 shows an example of an impulsive electron event with associated type III radio emission and *in situ* electron plasma waves (*Lin et al.,* 1981). The top panel shows the electric field intensities in four frequency channels from 17.8 to 100 Hz. The smooth intensity variations characteristic of a type III radio burst, consisting of a rapid rise followed by a slow monotonic decay, are clearly evident in the 56.2 and 100 kHz channels. The very intense irregular electric field intensity variations in the 31.1 kHz channel from about 20:00 to 21:30 UT are narrow band electron plasma (Langmuir) waves. Because of the filter overlap, somewhat weaker Langmuir wave intensities are also evident in the 17.8 and 56.2 kHz channels. The electron plasma frequency, f_{p-}, computed from the measured solar wind density of 7 cm^{-3}, is 24 kHz.

The large difference between the peak and average electric field intensities indicates that the Langmuir waves are very impulsive. Figure 4 shows the plasma wave

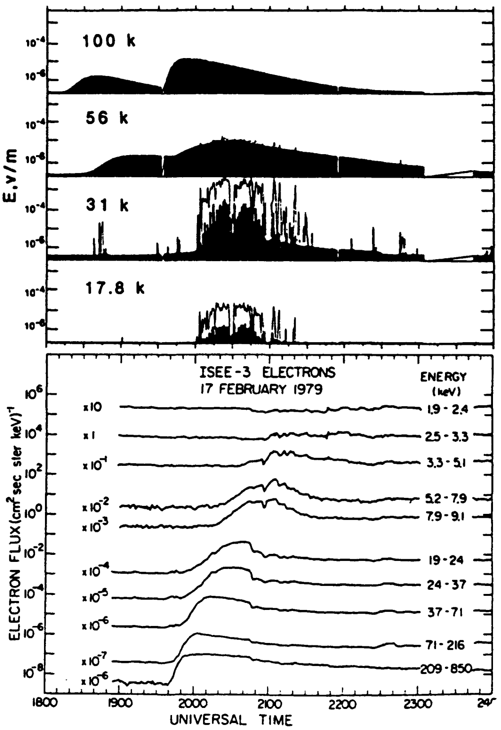

Figure 3. The top panel shows the electric field intensity measured from ISEE-3 (from *Lin et al.*, 1981) on 17 February, 1979 in four broad frequency bands for the event of interest. The black areas show the intensity averaged over 64 s. The solid lines give the peak intensity measured every 0.5 s. The smoothly varying profiles in the 100 and 56.2 kHz channels show two solar type III radio bursts. The second one is of interest here. The intense highly impulsive emissions observed in the 31.1 and 17.8 kHz channels are the electron plasma (Langmuir) waves. The lower panel shows the omnidirectional electron fluxes from 2 keV to >200 keV. Velocity dispersion is clearly evident.

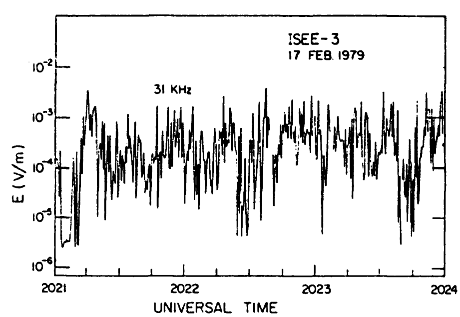

Figure 4. An expanded plot of the 31 kHz channel at 0.5 s resolution for 3 minutes near the maximum plasma wave intensity in the event. Note the extremely impulsive nature of the waves. The peak electric field appears to have an upper limit of 3–4 mV m^{-1}.

amplitude at 0.5 sec time resolution for three minutes near maximum. Intensity changes of over two orders of magnitude can occur within 0.5 s and single bursts rarely last more than one or two 0.5 s readouts. The peak amplitudes appear to be limited to a level of a few mV m^{-1}. These very impulsive fluctuations are characteristic of previous observations of Langmuir waves associated with type III radio bursts. Although more intense bursts have been observed closer to the Sun, this is one of the most intense Langmuir wave events observed at 1 AU.

The bottom panel of Figure 3 shows the spin-averaged low-energy electron intensities simultaneously detected by ISEE-3. The solar flare electrons are first detected above 200 keV energy at about 19:40 UT. Electrons are subsequently detected in progressively lower and lower energy channels at later and later times with very clear evidence of velocity dispersion. Simple comparison of the plasma wave and electron intensities suggests that the Langmuir waves are associated with electrons in the energy range of about 3 to 30 keV.

Figure 5 shows the measured pitch angle distributions for the electrons. Typically at energies above ~15 keV the FWHM of the pitch angle distribution is >60–80°. In contrast, the electrons below ~10 keV are much more beamlike with angular FWHM of <25°. This contrasting behavior of the >15 keV and <10 keV electrons is observed in most solar impulsive electron events. These data are used to construct the distribution of the electrons as a function of $v_\parallel$, their velocity parallel to the magnetic field. The electron distribution $f(\overline{v})$ is assumed to by gyrotropic. $f(\overline{v})$ is integrated over $v_\perp$ for all particles with a given $v_\parallel$ to obtain $f(v_\parallel)$. These are shown in Figure 6 at 5-minute intervals through the event. Each succeeding distribution is shifted to the right by 2×10^9 cm s^{-1} in velocity.

The solid dots in Figure 6*a* show $f(v_\parallel)$ for the background population just prior to the onset of the electron event. The level of this long non-thermal tail background population, which is observed at all times although at varying flux levels, is important in determining when a bump will form on the tail of the distribution. The electron distributions develop a well-defined bump-on-tail by ~2000 with the bump progressing to lower velocities with time. In contrast to the expectations of the inhomogeneous quasi-linear numerical models, there is no obvious plateauing of the bump.

There is good qualitative agreement between the Langmuir wave growth and the evolution of $\partial f/\partial v_\parallel$. The positive slopes are typically $\partial f/\partial v_\parallel \approx 10^{-28}-10^{-24}$ cm^{-5} sec^2 with width $\Delta v/v \approx 0.2-0.3$. $\partial f/\partial v_\parallel$ is greater than 10^{-25} cm^{-5} sec^2 for ~10 minutes at a given velocity. Since $\partial f/\partial v_\parallel > 10^{-25}$ cm^{-5} sec^2 implies a growth rate $\gamma \gtrsim 1$ sec^{-1} the plasma wave levels should have grown to far higher levels than those measured. At the observed wave levels the bump-on-tail in the electron distribution should have been plateaued in ~0.1 sec to ~1 min., much shorter than the ~10 minutes persistence time for the bump. These measurements indicate that the Langmuir waves have been shifted out of resonance with the electron beam.

EVIDENCE FOR NONLINEAR WAVE-WAVE INTERACTIONS

Various nonlinear wave-wave interactions have been suggested for shifting the plasma waves out of resonance with the electron beam (see *Goldman,* 1983, for review). In general, the dominant Langmuir wave transfer processes are those which involve a low-frequency excitation in addition to another Langmuir wave (*Tsytovich,* 1970). *Lin*

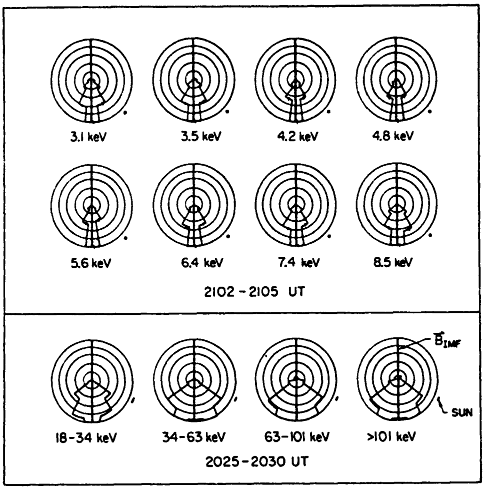

Figure 5. Polar plots of the pitch angle distributions for electrons in different energy intervals measured from ISEE-3 on 1979 February 17. Note the broad, >90° FWHM, flat-topped and sharp-sided distributions at energies above ~20 keV, as compared with the one-dimensional <25° FWHM beamlike character at low energies.

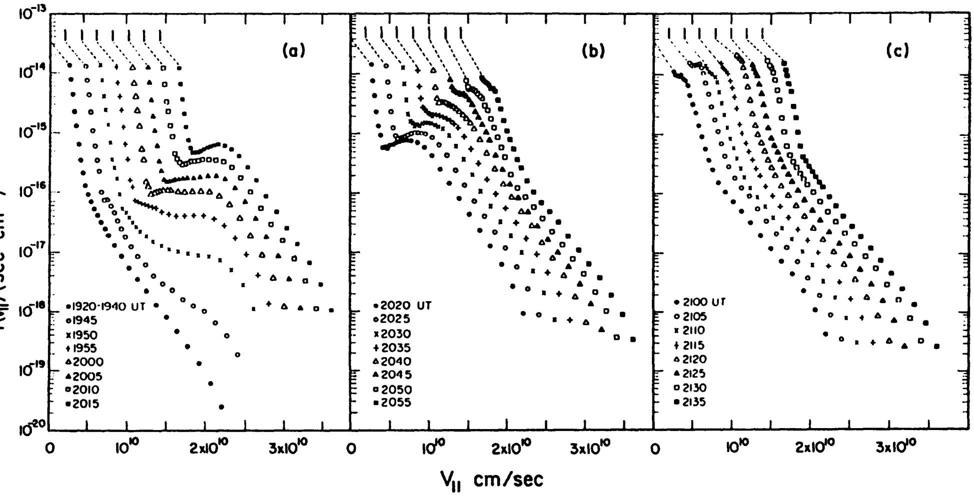

Figure 6. The comprehensive measurements over energy and angle taken from ISEE 3 on 1979 February 17 have been used to construct the one-dimensional velocity distribution function of the electrons every 64 s. The distribution averaged over 20 minutes prior to the event onset is indicated by the solid dots in panel *(a)*. The 64 s measurements of the distribution during the event are shown every 5 minutes. Note the positive slope which develops and moves to lower velocities with time.

et al. (1986) searched for low frequency fluctuations in association with the Langmuir waves observed in type III radio bursts by the ISEE-3 spacecraft. Figure 7 shows a type III solar radio burst with clearly associated Langmuir waves and energetic electrons. The smooth intensity variations characteristic of a type III radio burst, consisting of a rapid rise followed by a slow monotonic decay, are clearly evident in the 31.6, 56.2, and 100 kHz channels. The electron plasma oscillations are observed in the 17.8 kHz channel (with some overlap into the 10 kHz channel) from about 1110 to 1150 UT, in good temporal agreement with $f(v_\parallel)$ which exhibits a bump-on-tail from ~1109 to ~1142. The electron plasma frequency computed from the solar wind plasma density of ~2 cm^{-3} (Table I) is 12.7 kHz. From ~316 Hz down to 31.6 Hz there are highly impulsive bursts at the same time as the most intense bursts of Langmuir waves. In the 56.2 and 31.6 Hz channels, these are the only bursts detectable above the background.

Table I. Plasma, Beam, and Wave Parameters for 11 March 1989 Event

Solar wind plasma:[a]	
Solar wind density, n	2 cm^{-3}
Solar wind velocity, V_{SW}	480 km s^{-1}
Angle of magnetic field to solar wind, θ_B	139°
Electron temperature, T_e	2×10^5 K
Ion temperature, T_i	4×10^4 K
Debye length, λ_D	2.2×10^3 cm
Electron plasma frequency, f_{p-}	13 kHz
Ion plasma frequency, f_{p+}	3×10^2 Hz
Fast electrons:	
Beam velocity, v_b	~3.5×10^9 cm s^{-1}
Beam density, n_b	~7×10^{-5} cm^{-3}
Positive slope, $\partial f/\partial v_\parallel$	~10^{-25} cm^{-3} s^2
Beam width, $\Delta v_b/v_b$	~0.1–0.2
Langmuir pump waves:	
Beam resonant wave number, k_0	2.3×10^{-5} cm^{-1}
Maximum wave amplitude, $E_{0_{max}}$	~1 mV m^{-1}
Maximum normalized energy density, $W_{max}=E_0^2/8\pi n \kappa T_e$	8×10^{-7}
Long wavelength ion acoustic waves:	
Wavenumber, k_I (typical)	1.8×10^{-5} cm^{-1}
Ion acoustic speed, c_s	5.2×10^6 cm s^{-1}
Ion acoustic frequency, f_I	15 Hz
Maximum electric field, $E_{I_{max}}$	~40 μV m^{-1}

[a] Solar wind parameters provided by J. Gosling and W. Feldman, and magnetic field by B. Tsurutani, private communication (1984).

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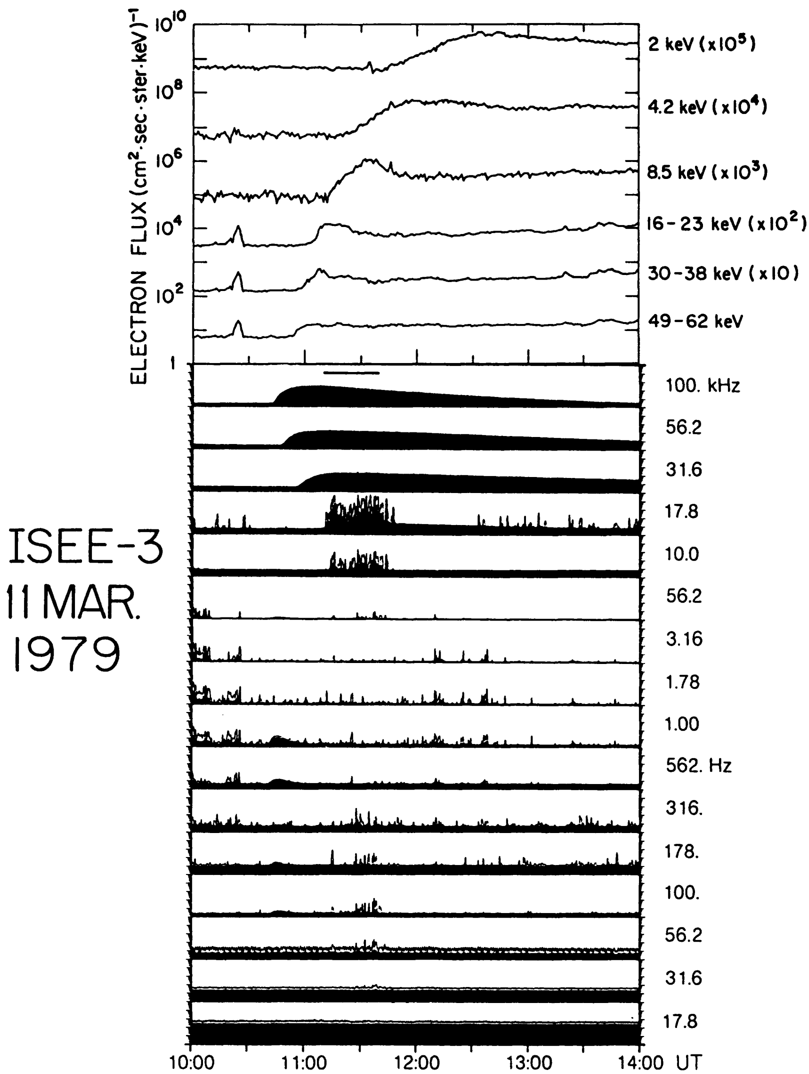

Figure 7. The top panel shows the spin-averaged flux of electrons from 2 to 62 keV for the type III solar radio burst of 11 March, 1979. The spike at 10:20 UT and smaller spikes which occur simultaneously in several energy channels are due to energetic particles flowing upstream from the Earth's bow shock. The lower panel shows the electric field intensity measured in 16 broadband channels from 100 kHz down to 17.8 Hz. The horizontal bar at the top indicates times of positive slope in the electron reduced velocity distribution [$f(v_{\parallel})$]. The smoothly varying profiles (100, 56.2, and 31.6 kHz) show the type III radio burst. The intense, highly impulsive emissions at 17.8 kHz and 10 kHz are electron plasma waves. The sporadic bursty emissions between 3.16 kHz and ~316 Hz have been previously identified as short wavelength ion acoustic waves. The impulsive emissions at frequencies from 316 to 31.6 Hz which occur from ~1115 to 1145 UT, simultaneous with the electron plasma waves, are believed to be long wavelength ion acoustic waves (from *Lin et al.*, 1986).

Figure 8 plots the highest time resolution (0.5 s) data for the 17.8 kHz Langmuir wave channel and the 100 Hz electric field channel for the period 1136–1140 UT. Most, but not all, of the Langmuir bursts which exceed ~0.1 mV m^{-1} are accompanied by a corresponding burst at 100 Hz. The maximum electric field at ~100 Hz is ~0.04 mV m^{-1}, almost two orders of magnitude above the background level. The fact that this low frequency noise is not observed in the 100 Hz magnetic channel suggests that it is a low-frequency electrostatic mode, most likely a long wavelength ion-acoustic wave.

Representative spectra of these low-frequency bursts are shown in Figure 9. the bursts show broad peaks at $f_I \sim 100$ Hz and very rapid cutoff at high frequencies; the 1/10 maximum point occurs at ~250 Hz. The frequency spectrum measured by the spacecraft is almost certainly determined by Doppler shifts, since the solar wind velocity is much larger than the phase velocity of all the known low-frequency electrostatic modes. If these are long-wavelength ion acoustic waves, Doppler-shifted by the solar wind velocity and aligned with the magnetic field, then their wave numbers k_I are

$$k_I \approx \frac{2\pi f_I}{V_{SW} \cos\theta_B + c_s},$$

where V_{SW} is the solar wind speed, c_s is the ion sound speed, and the angle between V_{SW} and the magnetic field is θ_B. For $f_I \approx 100$ Hz and the solar wind parameters in Table I, $k_I \approx 1.8\times10^{-5}$ cm^{-1}. The wave number of the ion acoustic waves is thus comparable to the wave number of the beam resonant Langmuir waves, $k_0 \approx 2.3\times10^{-5}$ cm^{-1}. Table I summarizes the parameters of the solar wind plasma, electron beam, and plasma waves.

Figure 10 plots the low-frequency wave amplitude versus the Langmuir wave amplitude for the bursts shown in Figure 8. As mentioned earlier, there are a few intense bursts of Langmuir waves which appear to have little or no effect above background at low frequencies (points at bottom right). For most Langmuir bursts the electric field of the correlated low-frequency burst appears to increase approximately linearly with Langmuir wave amplitude.

DISCUSSION

The close temporal correlation of the 30–300 Hz low frequency noise bursts with the most intense Langmuir wave bursts suggests that they are the result of a nonlinear wave-wave interaction. Theoretical work and numerical simulations suggest that strong turbulence phenomena such as modulational instability and self focusing of Langmuir waves (soliton collapse) should become important at a threshold of $W = E^2/8\pi nkT_e \approx 10^{-5}$, where E is the Langmuir wave electric field (see *Goldman,* 1983, for review). The 11 March 1979 event (Table I), as well as almost all the type III events observed at 1 AU, however, have maximum values of W substantially below 10^{-5}. In addition, the low frequency wave spectrum associated with modulational instability appears inconsistent with the observed spectrum (*Lin et al.,* 1986). Although very intense plasma waves confined to very small spatial regions might be missed by the plasma wave instrument, it appears unlikely that strong turbulence phenomena play

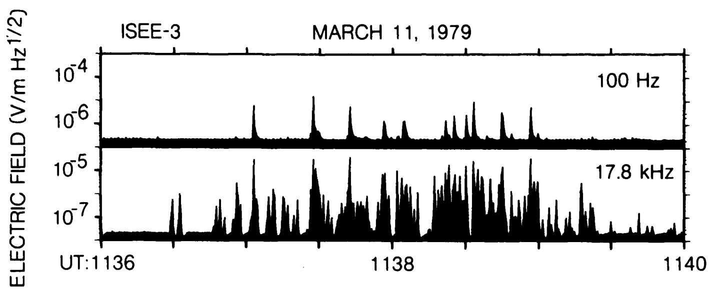

Figure 8. High time resolution (0.5 s) plots of the Langmuir wave channel (17.8 kHz) and the 100 Hz long-wavelength ion acoustic wave channel for the 11 March, 1979 event (from *Lin et al.*, 1986). Note the close correspondence between the most intense Langmuir wave spikes and the 100 Hz spikes.

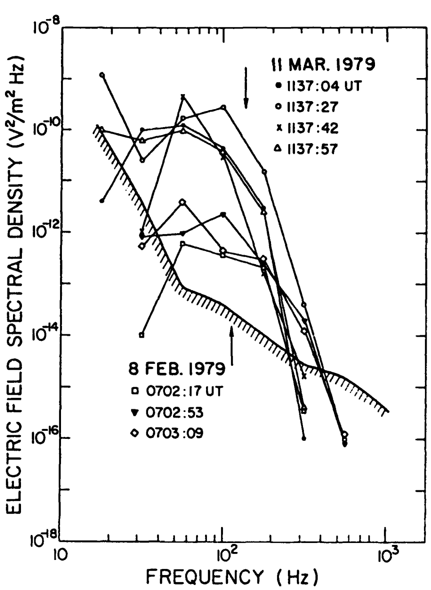

Figure 9. Spectra of the low-frequency bursts which are coincident with the intense Langmuir wave spikes. Background levels are shown by the hatched line. Each spectrum is taken at a single 0.5 s point. The arrows indicate the frequency at which ion acoustic waves would be observed in the spacecraft frame if they had wave number equal to that of the beam resonant Langmuir waves.

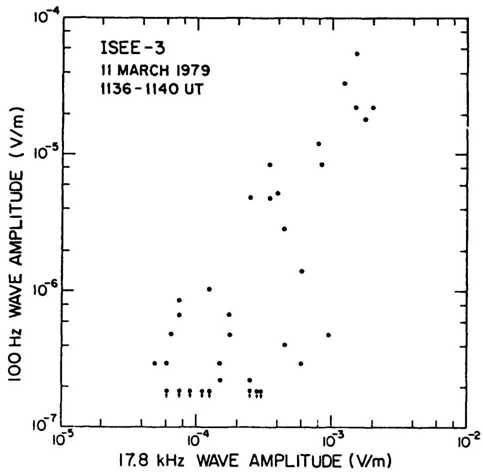

Figure 10. Peak electric field amplitude measured in the low-frequency (100 Hz) channel vs. the Langmuir wave (17.8 kHz) amplitude for the bursts of Fig. 8.

a significant role in type III bursts with the possible exception of a few very intense events.

If the low frequency bursts observed simultaneously with type III Langmuir wave bursts are due to long wavelength ion acoustic waves, these waves will not be very strongly damped because $T_e/T_i \approx 5$ (Table I). Thus a parametric decay instability, rather than induced scattering, might be the appropriate description of the situation for type III radio bursts observed at 1 AU.

Two three-wave decay processes appear relevant: the decay of a pump Langmuir wave into a daughter Langmuir wave and an ion acoustic wave, $L \rightarrow L' + I$; and into a daughter transverse electromagnetic wave and an ion acoustic wave, $L \rightarrow T + I$. The low frequency wave spectrum would be consistent with either of these decay processes. The transverse waves from the electromagnetic decay process would provide a natural source for type III radio burst emission at the fundamental, i.e., near f_{p-}. *Kellogg* (1980) and *Dulk et al.* (1984) find that the radio emission at the onset of interplanetary type III is most likely at the fundamental.

Detailed calculations show that the threshold for the electrostatic decay instability, for parameters of Table I, is about an order of magnitude higher than the observed Langmuir wave levels. The threshold for the electromagnetic decay instability, if one ignores convective effects, is very low and easily exceeded by typical type III events. If the instability is convective, then the large group velocity of the electromagnetic waves may severely limit the growth of both the ion acoustic and transverse waves. It would be difficult in this case to interpret the observed low-frequency bursts in terms of an electromagnetic decay instability. Alternatively, the electromagnetic wave energy might be localized by solar wind density fluctuations; either through wave trapping by refraction in large-scale density fluctuations (*McDonald,* 1983), or wave localization by cumulative phase reinforcement due to multiple scattering by random, small-scale density fluctuations (*Escande and de Genouillac,* 1978; *Escande and Souillard,* 1984; *Levedahl,* 1987).

The density inhomogeneities observed in the solar wind (*Celnikier et al.,* 1983; 1987) may also strongly affect the growth rate of the Langmuir waves. *Muschietti et al.* (1985) showed that the effective damping rate due to angular diffusion of the Langmuir waves by the observed density fluctuations exceeds the growth rate inferred from the particle data. The clumpy character of the Langmuir waves may reflect the fact that the waves can be amplified only along certain favored paths (*Smith and Sime,* 1979).

In an attempt to reconcile these observations with the present theoretical models of the plasma processes for type III bursts, *Melrose and Goldman* (1987) proposed that there are localized microstructures where $\partial f/\partial v_\parallel$ is larger than those measured by a factor of $\gtrsim 10^2$. These microstructures would pass by the spacecraft on time scales of $\lesssim 1$ sec, so the present electron distribution measurements, which have a temporal resolution of ~1 minute, will miss them. The proportionately larger growth rates implied by such $\partial f/\partial v_\parallel$ would overcome the damping by density fluctuations and allow growth to an initial level of Langmuir waves above the threshold for electrostatic decay instability and perhaps also above the threshold for modulational instability and soliton collapse.

The microstructures develop because of the threshold for wave growth imposed by the density fluctuations. Velocity dispersion will tend to steepen positive $\partial f/\partial v_\parallel$

with time until it exceeds that threshold; then waves will grow very rapidly to high intensities. These waves then plateau the electron distribution, slowing down the fast electrons to provide a local enhancement of the fast electron density. The cycle then can start all over.

New, much faster measurements will be required to test these ideas. Experiments currently being developed for the International Solar Terrestrial Physics (ISTP) Global Geospace Science (GGS) mission Wind spacecraft, to be launched in late 1992, will have the capability to measure the electron distribution function in the region of the bump-on-tail with temporal resolution of $\lesssim 10^2$ ms. Furthermore, a wave-particle correlator will search for bunching of the beam electrons in the wave electric field. If the waves are resonance with the beam (see Figure 2*a*) then the electrons should bunch in phase with the wave. If the electrons are losing energy to the wave the peak of the electron bunching should be on the ascending portion of the wave. These measurements should provide a new window on the wave-particle and wave-wave processes in type III bursts.

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REFERENCES

Alvarez, H., F. T. Haddock, and R. P. Lin, *Solar Phys.* **26**, 468, 1972.
Bardwell, S., and M. V. Goldman, *Astrophys. J.* **209**, 912, 1976.
Celnikier, L. M., C. C. Harvey, R. Jegou, M. Kemp, and P. Moricet, *Astron. Astrophys.* **126**, 293, 1983.
Celnikier, L. M., L. Muschietti, and M. V. Goldman, *Astron. Astrophys.* **181**, 138, 1987.
Dulk, G. A., J. L. Steinberg, and S. Hoang, *Astron. Astrophys.* **141**, 30, 1984.
Escande, D. F., and G. V. de Genouillac, *Astron. Astrophys.* **68**, 405, 1978.
Escande, D. F., and B. Souillard, *Phys. Rev. Lett.* **52**, 1297, 1984.
Frank, L. A., and D. A. Gurnett, *Solar Phys.* **27**, 446, 1972.
Ginzburg, V. L., and V. V. Zheleznyakov, *Sov. Astron.–AJ* **2**, 653, 1958.
Goldman, M. V., *Solar Phys.* **89**, 403, 1983.
Goldman, M. V., *Rev. Mod. Phys.* **55**, 709, 1984.
Goldman, M. V., and D. F. DuBois, *Phys. Fluids* **25**, 1062, 1982.
Grognard, R. J.-M., *Solar Phys.* **81**, 173, 1980.
Gurnett, D. A., and R. R. Anderson, *Science* **194**, 1159, 1976.
Gurnett, D. A., and R. R. Anderson, *J. Geophys. Res.* **82**, 632, 1977.
Kaplan, S. A., and V. N. Tsytovich, *Sov. Astron.–AJ* **11**, 956, 1968.
Kellogg, P. J., *Astrophys. J.* **236**, 696, 1980.
Levedahl, K., Ph.D. thesis, University of California, Berkeley, 1987.
Lin, R. P., *Solar Phys.* **12**, 266, 1970.

Lin, R. P., *Space Sci. Rev.* **16**, 189, 1974.
Lin, R. P., L. G. Evans, and J. Fainberg, *Astrophys. Letters* **14**, 191, 1973.
Lin, R. P., D. W. Potter, D. A. Gurnett, and F. L. Scarf, *Astrophys. J.* **251**, 364, 1981.
Lin, R. P., W. K. Levedahl, W. Lotko, D. A. Gurnett, and F. L. Scarf, *Astrophys. J.* **308**, 954, 1986.
Magelssen, G. R., and D. F. Smith, *Solar Phys.* **55**, 211, 1977.
McDonald, S. W., Ph.D. thesis, University of California, Berkeley, 1983.
Melrose, D. B., and M. V. Goldman, *Solar Phys.* **107**, 329, 1987.
Muschietti, L., M. V. Goldman, and D. Newman, *Solar Phys.* **96**, 181, 1985.
Nicholson, D. R., M. V. Goldman, P. Hoyng, and J. C. Weatherall, *Astrophys. J.* **225**, 605, 1978.
Papadopoulous, K., *Phys. Fluids* **18**, 1979, 1975.
Papadopoulous, K., M. L. Goldstein, and R. A. Smith, *Astrophys. J.* **190**, 175, 1974.
Russell, D. A., and M. V. Goldman, *Phys. Fluids* **26**, 2717, 1983.
Smith, D. F., and D. Sime, *Astrophys. J.* **233**, 998, 1979.
Sturrock, P. A., *AAS-NASA Symposium on the Physics of Solar Flares*, ed. W. N. Hess (NASA SP-50), p. 357, 1964.
Takakura, T., and H. Shibahashi, *Solar Phys.* **46**, 323, 1976.
Tsytovich, V. N., *Nonlinear Effects in Plasmas*, New York, Plenum, 1970.
Wild, J. P., *Australian J. Sci. Res.* **A3**, 541, 1950*a*.
Wild, J. P., *Australian J. Sci. Res.* **A3**, 399, 1950*b*.
Zakharov, V. E., *Soviet Phys.–JETP* **35**, 908, 1972.

DISCUSSION

MONTGOMERY: The velocity-space distribution you are talking about is the one-dimensional velocity distribution function, $f_e(v_{||})$. This is an integral of the fully three-dimensional distribution $f_e(\mathbf{v})$. I do not have a good picture of the three-dimensional presumed behaviour of $f_e(\mathbf{v})$. Alterations of $f_e(\mathbf{v})$ which "flatten" (stabilize) it for one direction of **k** often destabilize it for some other direction of **k**. Can you be sure that an $f_e(\mathbf{v})$ exists that has the properties you require of it, and if so, could you speculate upon what it looks like?

LIN: We have constructed the 3-D distribution from our angular measurements assuming gyrotropy. This has then been integrated to obtain $f_e(v_{||})$. We do not see a truly plateaued (flat) $f_e(v_{||})$ and we have not analyzed the 3-D distribution in detail yet.

HOLLWEG: Are there proxy indicators for the presence of the intense Langmuir clumps? For example, how much would they scatter the background (thermal) solar wind electrons, and could the consequent isotropization of f be observed?

LIN: The effect of these Langmuir clumps on the thermal solar wind electrons would be minimal and probably unobservable, unless the wave levels are much more intense than presently measured.

KUNDU: (i) How valuable will it be to conduct similar experiments near the Sun, for example with a solar probe?

(ii) What would you expect to happen, when we make similar experiments at about 4 solar radii, especially from the point of view of conversion of electrostatic waves into electromagnetic waves?

LIN: (i) It would be extremely interesting to conduct similar experiments close to the Sun. It may be that conditions change rather drastically with distance. Certainly the type III radio emissivity varies substantially with frequency.
(ii) I can only speculate that with the very different conditions at $4R_0$ the conversion mechanisms could be quite different.

VAN BALLEGOIJEN: The background electron distribution shows a non-thermal tail. Do these tail electrons contribute significantly to the heat flux?

LIN: The non-thermal tail above 5 keV generally does not contribute a large fraction of the total electron heat flux.

LANG: How often do type III bursts on the Sun generate electron beams that reach the vicinity of the Earth? A related question is how long was the ISEE-3 spacecraft in outer space detecting these events? You showed two events detected ten years ago in 1979, so one wonders if these are typical of many such events actually detected.

LIN: Our ISEE-3 experiment operated continuously in the interplanetary medium for about 15 months. Over 300 impulsive electron events were obtained, each of which is associated with interplanetary type III bursts.

KRISHAN: While studying parametric instabilities, have you considered the broad-band nature of the pump, for it would raise the thresholds and lower the growth-rates?

LIN: We have not considered the broad-band nature of the pump. It would be interesting to see how the thresholds and growth rates would change.

HOYNG: What is the physical origin of the microstructures postulated by Melrose and Goldman (1987).

LIN: Melrose and Goldman assumed an initially spatially localized group of electrons. As they free-stream along the field line a positive slope grows larger, but since there are ambient density fluctuations, the growth of Langmuir waves is suppressed until the positive slope exceeds a threshold. At that point Langmuir waves grow rapidly to large amplitudes and plateau the electrons. In the process of plateauing the electrons are bunched spatially. The entire sequence then repeats.

SEMIKOZ: You have just shown some elementary processes for *strong* turbulence, particularly you have shown a decay instability ($t \rightarrow \ell + s$, *etc.*). I have not seen the induced Compton process (type: $\ell + t \rightarrow \ell + t$) with a four-waves interaction. Why?

LIN: We have only treated the simple 3-wave decay processes. Perhaps 4-wave processes should also be considered. However, the low-frequency waves are only observed coincident with the most intense Langmuir spikes, and are not present otherwise.

GANGADHAVI: Do you expect a parametric decay of radio waves into electron and ion Langmuir waves in the interplanetary medium and corona?

GANGADHAVI: Do you expect a parametric decay of radio waves into electron and ion Langmuir waves in the interplanetary medium and corona?

LIN: I suspect that the threshold for this decay is probably too high in the interplanetary medium, but this has to be calculated.